

Observation of Σ_b^\pm at CDF

(or states consistent with Σ_b^\pm)

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All Experimenters' Meeting
Special Topic



Motivation

Why spectroscopy?

- hadron mass measurements allow to check predictions of QCD inspired quark models:
 - potential models
 - lattice QCD calculations
 - $1/N_c$ expansion models
- studies of bottom hadrons in particular test predictions of HQET
- HQET has been quite successful in describing the properties of heavy mesons. What about baryons, a more complex 3-quark system?
- experimentally it is fun to find new states



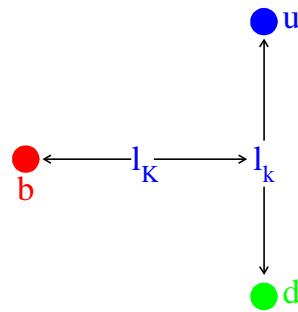
Motivation

- Tremendous progress in spectroscopy
 - B^{**} is well established
 - B_s^{**} observed (first observation by D0)
 - observed fully reconstructed $B_c^+ \rightarrow J/\psi \pi^+$
- Still, there is only one well established B-baryon – Λ_b
- Next readily observable B-baryon - Σ_b :
 - decays strongly $\Sigma_b \rightarrow \Lambda_b \pi$, low Q expected, narrow state(s)
 - expect significant sample of Λ_b ; about 3,000 in $1fb^{-1}$
 - CDF is in the unique position to be the first here:
 - displaced track trigger for fully hadronic modes
 - excellent track momentum resolution (\Rightarrow excellent mass resolution) thanks to the 138 cm lever arm tracker in 1.4 T solenoidal field
 - precision vertexing thanks to SVXII
- expect to observe lowest lying charged Σ_b states, measure their masses and possibly isospin splittings



What is Σ_b ?

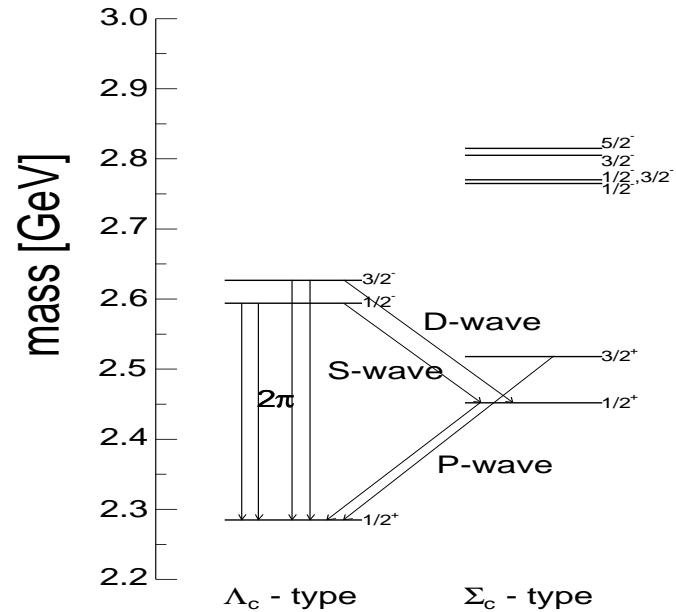
- similar to Σ_c



- Λ -type $Q \underbrace{[q_1 q_2]}_{\bar{3}}$ Σ -type $Q \underbrace{\{q_1 q_2\}}_6$,
- ground states $l_k = 0, l_K = 0$:

$$j_I = s_I = 1$$

$$J = j_I \pm s_Q \begin{cases} \frac{3}{2}^+ \\ \frac{1}{2}^+ \end{cases} \left\{ \begin{array}{c} \Sigma_b^* \\ \Sigma_b \end{array} \right\} \text{ degenerate for } m_Q \rightarrow \infty$$



$$\frac{M(\Sigma_b^*) - M(\Sigma_b)}{M(\Sigma_c^*) - M(\Sigma_c)} = \frac{M(B^*) - M(B)}{M(D^*) - M(D)} = 0.33,$$

$$M(\Sigma_c^*) - M(\Sigma_c) \sim 70 \text{ MeV}$$

$$M(\Sigma_b^*) - M(\Sigma_b) \sim 23 \text{ MeV}$$

$$M(\Sigma_b) - M(\Lambda_b) \sim 180 - 190 \text{ MeV}$$

$$\Gamma(\Sigma_b) \sim 8 \text{ MeV}, \Gamma(\Sigma_b^*) \sim 17 \text{ MeV}$$

$$M(\Sigma_b^-) - M(\Sigma_b^+) = 5 - 6 \text{ MeV}$$

Analysis Strategy

- pre-select $\Lambda_b \rightarrow pK\pi$ candidates satisfying displaced trigger requirements (2/4 tracks) and loose vertex fit requirements
- optimize cuts to achieve best $S/\sqrt{S+B}$ Λ_b signal
- attach fifth track to form $\Sigma_b^\pm \rightarrow \Lambda_b^0\pi^\pm$ candidates
- measure Q-value spectrum:

$$Q = M(\Lambda_b\pi) - M(\Lambda_b) - m_\pi$$

to get rid of Λ_b mass systematic uncertainty

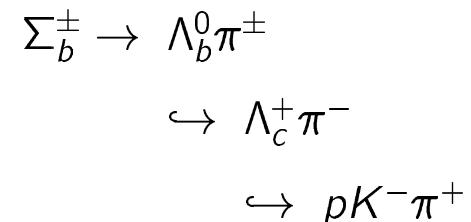
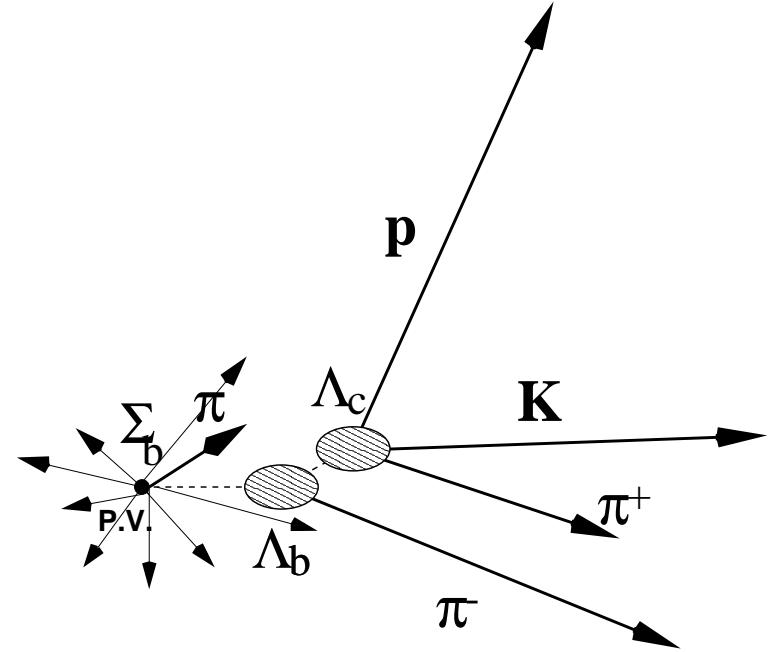
- blind "Signal Region":

$$0.03 < Q < 0.1 \text{ GeV}/c^2$$

choice is based on theoretical estimates

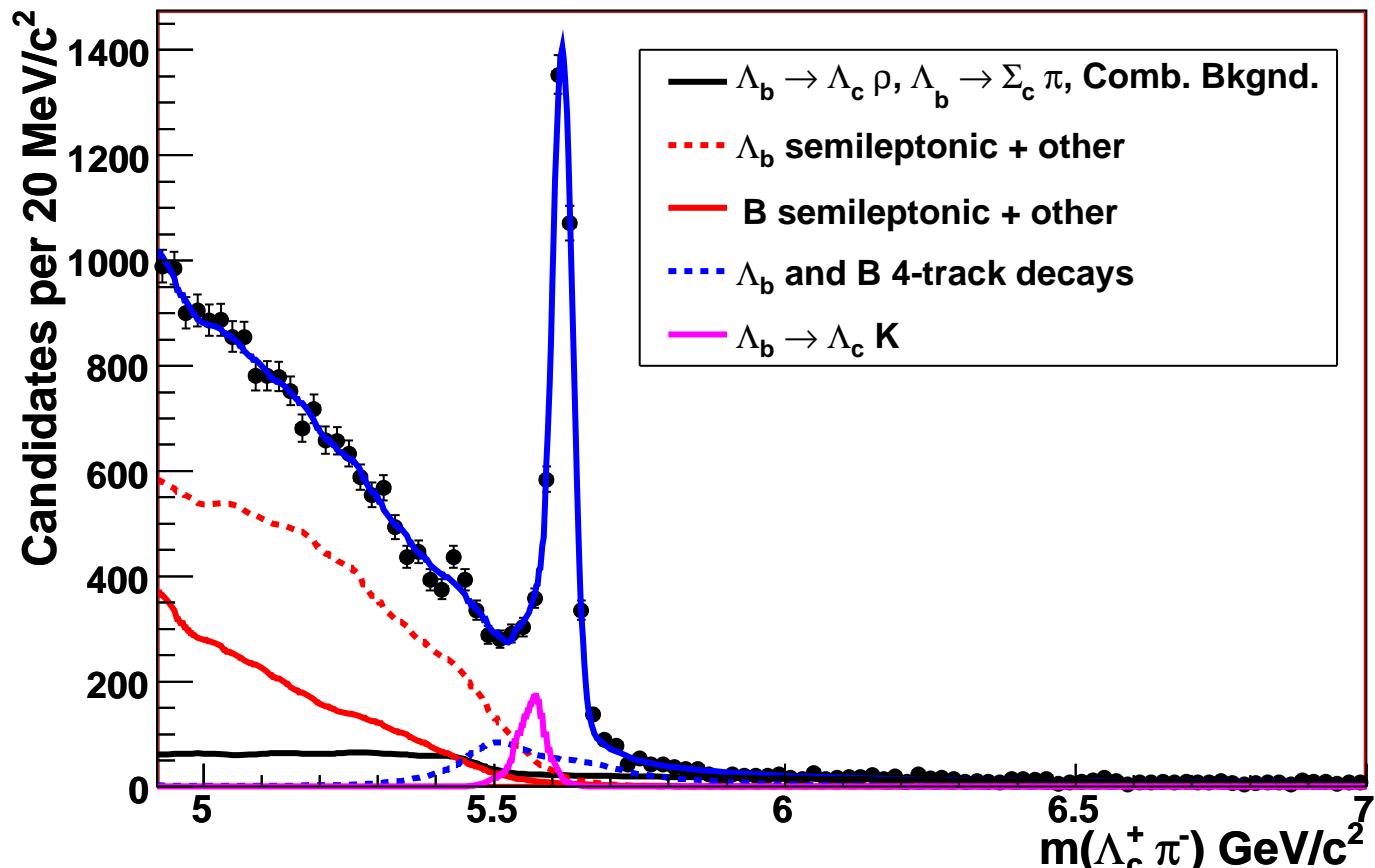
- optimize cuts on Σ_b candidates by scoring $S/\sqrt{1.5+B}$ in a blind fashion by taking "B" from Σ_b extrapolated sidebands: left sideband : $0 < Q < 0.03 \text{ GeV}/c^2$
- right sideband : $0.1 < Q < 0.5 \text{ GeV}/c^2$

- take "S" from PYTHIA Monte Carlo



Λ_b Signal in $1fb^{-1}$

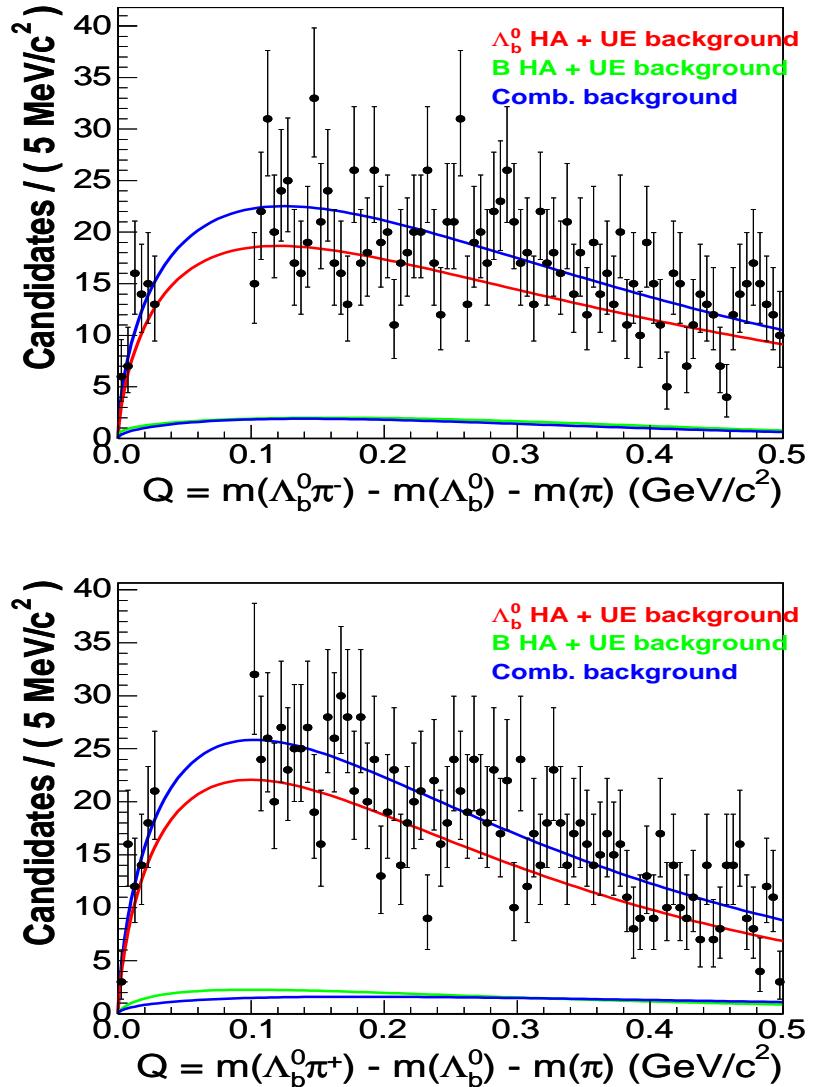
CDF II Preliminary, $L = 1.1 fb^{-1}$



projection of unbinned max log-likelihood fit

- about 3,000 Λ_b candidates in $\int \mathcal{L} dt = 1070 \pm 60 pb^{-1}$
- world's largest Λ_b sample

Blinded Q-plots



Cuts:

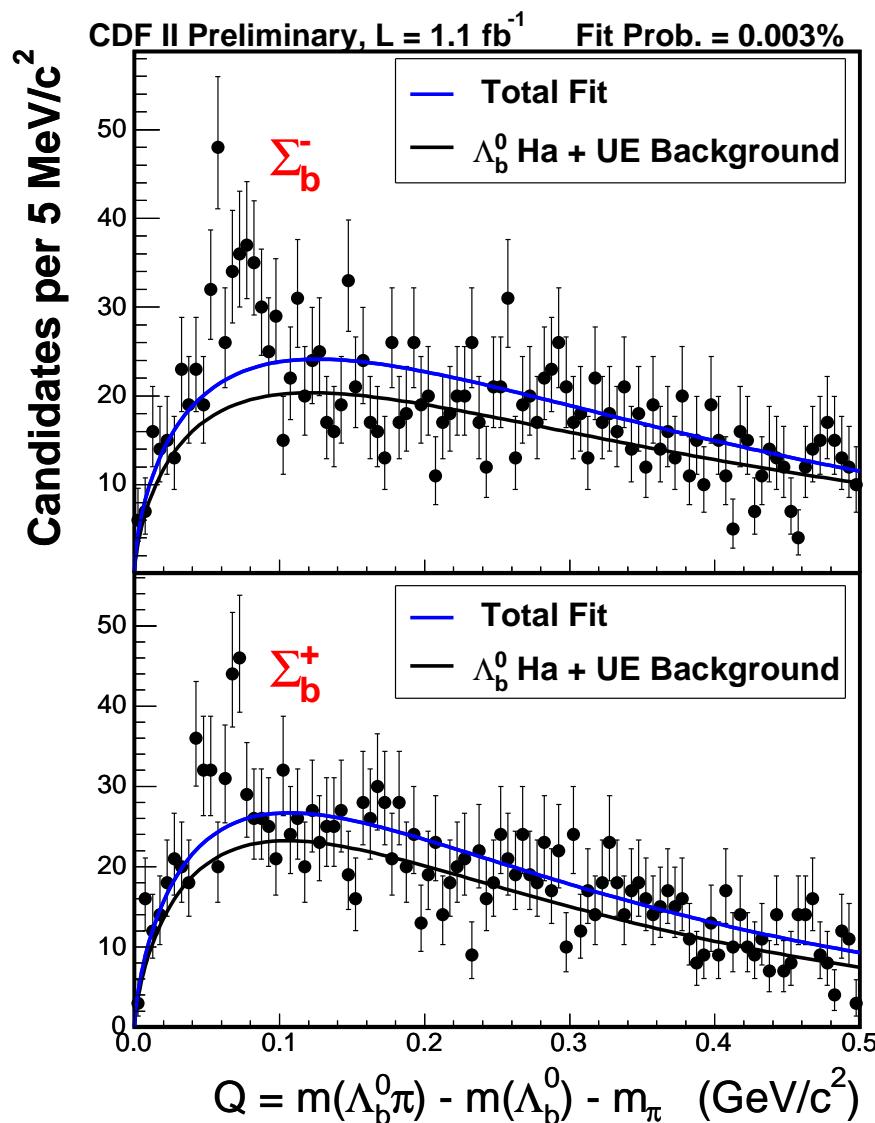
- $p_T(\Sigma_b) > 9.5 \text{ GeV}/c$
- $|d_0/\sigma_{d_0}| < 3$ (slow π track)
- $\cos\theta^* > -0.35$ (θ^* angle between slow π momentum in Σ_b rest frame and direction of Σ_b boost)

Backgrounds :

- "real" Λ_b plus random soft track from b-quark hadronization of underlying event
 Λ_b HA+UE background, a major background (Monte Carlo simulation)
- "real" B-meson faking Λ_b plus random soft track from b-quark hadronization or underlying event
B HA+UE background (Monte Carlo simulation)
- Combinatorial background (estimated using upper Λ_b sideband $5.8 < M(\Lambda_c \pi) < 6 \text{ GeV}/c^2$)

Shapes and relative normalization of background contributions were determined prior to opening the box

Open Box



- count observed candidates in the signal region
- compare with background extrapolation

sample	$S + B$	B	S	$S/\sqrt{S + B}$
$\Lambda_b^0 \pi^-$	416	268	148	7.3
$\Lambda_b^0 \pi^+$	306	298	108	5.4

- CDF does not bless $S/\sqrt{S + B}$
- there is a significant excess in the signal region in both spectra!
- proceed to fit adding signal terms:

$$G \otimes BW(Q, Q_{\Sigma_b}, \sigma_{\Sigma_b}, \Gamma_{\Sigma_b}) +$$

$$G \otimes BW(Q, Q_{\Sigma_b^*}, \sigma_{\Sigma_b^*}, \Gamma_{\Sigma_b^*})$$

for all four $\Sigma_b^{(*)\pm}$ states

- simultaneous unbinned maximum log-likelihood:
 - background shapes frozen
 - 7 floating variables – $Q_{\Sigma_b^-}, Q_{\Sigma_b^+}, Q_{\Sigma_b^*}, Q_{\Sigma_b}, N(\Sigma_b^-), N(\Sigma_b^*), N(\Sigma_b^+), N(\Sigma_b^{*+})$
 - detector resolutions and natural widths fixed.

Fit Result

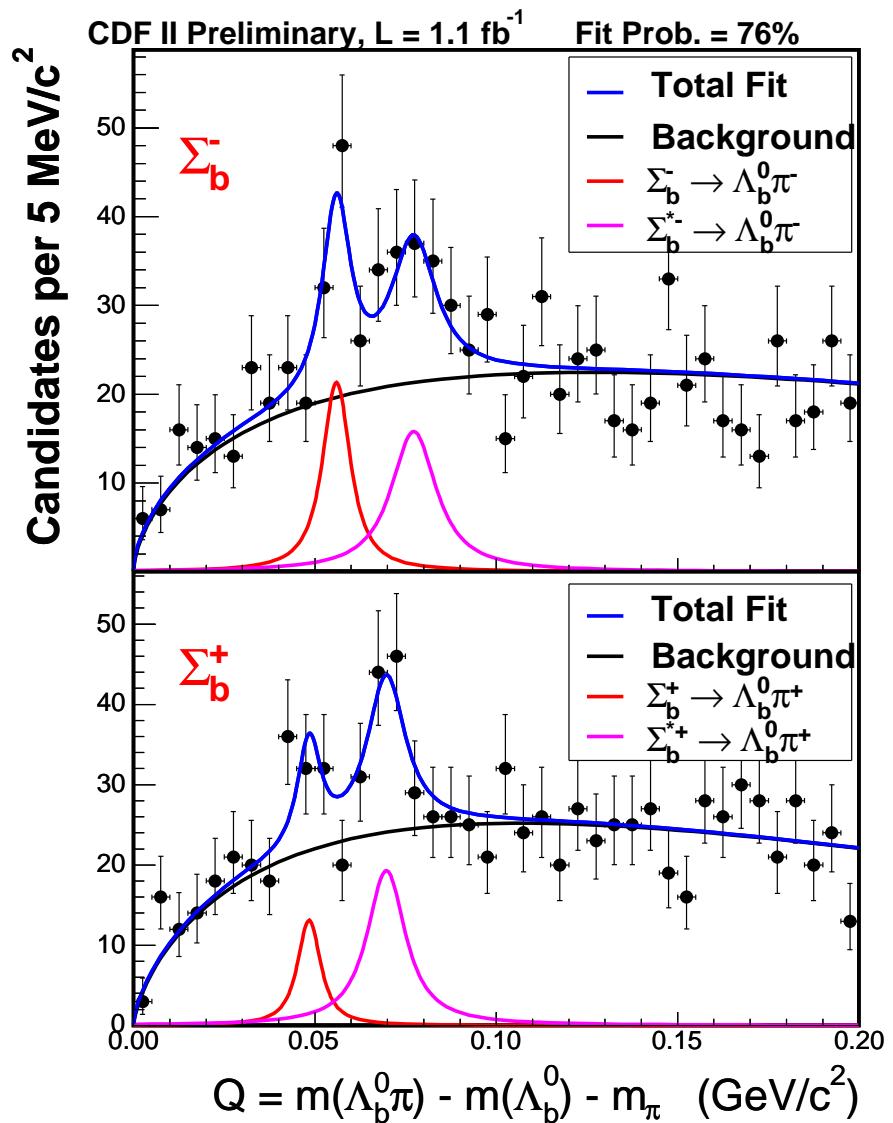
Yields:

$$N(\Sigma_b^-) = 60.0^{+14.8}_{-13.8} (\text{stat})^{+8.4}_{-4.0} (\text{syst})$$

$$N(\Sigma_b^+) = 29.0^{+12.4}_{-11.6} (\text{stat})^{+5.0}_{-3.4} (\text{syst})$$

$$N(\Sigma_b^{*-}) = 74.0^{+18.2}_{-17.4} (\text{stat})^{+15.6}_{-5.0} (\text{syst})$$

$$N(\Sigma_b^{*+}) = 74.0^{+17.2}_{-16.3} (\text{stat})^{+10.3}_{-5.7} (\text{syst})$$





Masses

$$M(\Sigma_b^-) - M(\Lambda_b) - M(\pi) = 55.9^{+1.0}_{-1.0}(stat) \pm 0.1(syst) \text{ MeV}/c^2$$

$$M(\Sigma_b^+) - M(\Lambda_b) - M(\pi) = 48.4^{+2.0}_{-2.3}(stat) \pm 0.1(syst) \text{ MeV}/c^2$$

$$M(\Sigma_b^*) - M(\Sigma_b) = 21.3^{+2.0}_{-1.9}(stat)^{+0.4}_{-0.2}(syst) \text{ MeV}/c^2$$



Conclusion/Outlook

- with $1fb^{-1}$ of luminosity accumulated, the CDF is finally in the flavor frontier mode. Hats off to Accelerator Division and excellent CDF operations.
- collected world largest sample of $\Lambda_b \rightarrow \Lambda_c \pi$ decays
- using this sample we observe 4 new states consistent with being lowest lying charged $\Sigma_b^{(*)}$ baryons
- we report measurement of masses of the new states (reported today at Beauty 2006)

Using CDF measurement $M(\Lambda_b) = 5619.5 \pm 1.2(stat) \pm 1.2(syst) \text{ MeV}/c^2$ (Phys. Rev. Lett. 96, 202001, 2006)

$$M(\Sigma_b^-) = 5816_{-1.0}^{+1.0}(stat) \pm 1.7(syst) \text{ MeV}/c^2$$

$$M(\Sigma_b^+) = 5808_{-1.0}^{+1.0}(stat) \pm 1.7(syst) \text{ MeV}/c^2$$

$$M(\Sigma_b^{*-}) = 5837_{-2.3}^{+2.0}(stat) \pm 1.7(syst) \text{ MeV}/c^2$$

$$M(\Sigma_b^{*+}) = 5829_{-1.8}^{+1.6}(stat) \pm 1.7(syst) \text{ MeV}/c^2$$

- as statistic grows, expect to measure the widths of $\Sigma_b^{(*)}$ baryons
- There will be Wine&Cheese on Oct 20 with all the gory details



Back up slides



Σ_b Systematics

Parameter	Tracking	Λ_b Sample Comp.	Λ_b Sample Norm.	Λ_b HA+UE Shape	Λ_b HA+UE Reweight	Detector Res.	Σ_b Width	Total
$Q_{\Sigma_b^-}$ [MeV/ c^2]	+0.06 -0.06	+0.00 -0.03	+0.009 -0.002	+0.000 -0.011	+0.04 -0.00	+0.00 -0.01	+0.009 -0.005	+0.07 -0.07
$Q_{\Sigma_b^+}$ [MeV/ c^2]	+0.06 -0.06	+0.03 0.00	+0.013 -0.013	+0.013 -0.000	+0.00 -0.11	+0.000 -0.014	+0.01 -0.02	+0.07 -0.13
$Q_{\Sigma_b^-} - Q_{\Sigma_b^+}$	+0.06 -0.06	+0.05 -0.00	+0.14 -0.13	+0.04 -0.00	+0.32 -0.00	+0.02 -0.00	+0.07 -0.07	+0.37 -0.16
$N(\Sigma_b^-)$	+0.0 -0.0	+0.7 0.0	+2.2 -2.2	+0.3 -0.0	+7.4 -0.0	+0.3 -0.0	+3.4 -3.4	+8.5 -4.0
$N(\Sigma_b^+)$	+0.0 -0.0	+3.3 0.0	+2.1 -2.1	+1.2 -0.0	+2.3 -1.8	+0.3 -0.0	+1.8 -2.0	+5.0 -3.4
$N(\Sigma_b^{*-})$	+0.0 -0.0	+0.4 0.0	+4.8 -4.7	+0.3 -0.0	+14.7 -0.00	+0.1 -0.0	+1.7 -1.7	+15.6 -5.0
$N(\Sigma_b^{*+})$	+0.0 -0.0	+7.3 -0.0	+4.8 -4.8	+2.8 -0.0	+4.6 -2.9	+0.2 -0.0	+0.8 -0.8	+10.3 -5.7



Σ_b Fit Likelihood Ratios

Hypothesis	ΔNLL	$1/LR$
"NULL" vs "4 peak"	44.7	$2.6 \cdot 10^{19}$
"2 Peak" vs "4 peak"	14.3	$1.6 \cdot 10^6$
"No Σ_b^- peak"	10.4	$3.3 \cdot 10^4$
"No Σ_b^+ peak"	1.1	3
"No Σ_b^{*-} peak"	10.1	$2.4 \cdot 10^4$
"No Σ_b^{*+} peak"	9.8	$1.8 \cdot 10^4$

